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Multi-Band Resonant Photonic Crystal Antenna for 5G Applications

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***Abstract*—Extended reality (XR) is bridging the gap between virtual and real-world interactions enabling users to interact in realistic virtual worlds, removing physical obstacles, and establishing shared areas that promote greater comprehension and teamwork. The growing demand for high-frequency 5G communication systems supporting these new applications motivates the need of compact and efficient antennas capable of operating at millimeter-wave frequency bands. This work explores how the use of photonic crystal (PhC) leverages the properties of a multi-band antenna operating within the 27.0 GHz and 41.49 GHz resonant bands. The High-Frequency Structure Simulator (HFSS) software is utilized in this paper to outline a comprehensive design and modeling approach for the proposed microstrip patch antenna.The design process involves optimizing the geometry and periodicity of the PhC structure to obtain resonant modes at the desired frequency bands by exploiting its bandgap properties, whilst enabling high quality resonances within the targeted frequency bands. The electromagnetic simulations and numerical analysis results demonstrate that the designed multi-band PhC-based antenna achieves a gain of 9.57 dBi. The resonant modes exhibit high quality factors, resulting in improved radiation efficiency. The proposed PhC-based antenna compact size, high gain, and multiple resonant bands make it suitable for a wide range of applications, including next-generation wireless communication systems supporting XR, radar systems, or satellite communications in the upper frequency bands.**

***Index Terms*—Photonic Crystal Antenna, Multi-Band Resonance, 5G Communication, Millimeter-Wave Bands, High Gain.**

I. Introduction

The continuous evolution of wireless communication networks are integral to the seamless integration of immersive experiences in Extended Reality (XR), [1]. XR, encompassing Augmented Reality (AR), [2], Virtual Reality (VR), [3], and Mixed Reality (MR), [4], merge physical and digital environments to create captivating and interactive experiences. XR denotes the seamless fusion of the virtual environment with the physical world [5]. These applications cover a diverse range of sectors, including entertainment, education, and training. As the demand for high data throughput and low-latency connectivity grows, the development of specialized antennas become crucial to meet the unique requirements of XR devices. VR is designed to deliver a fully engaging encounter within a simulated environment, whereas AR is focused on integrating virtual elements into the real world. MR represents an evolving paradigm aiming to establish a cohesive environment with seamless interactions between the physical and virtual realms. Beyond these fundamental concepts, the roots of XR can be traced back to the 1960s with the introduction of diverse VR and AR devices, such as the Sensorama VR machine [6] and Sword of Damocles AR machine [7]. The continuous advancement of computer and simulation technologies over time has winned the progress of VR and AR. With the increasing portability of today's devices, end-users (UEs) can now partake in a more immersive experience.

XR finds extensive application not only in consumer entertainment, including cultural performances, exhibitions, films, and live events, but is also progressively making inroads into vertical sectors such as medical care, education, and industry [8], [9]. Experiencing considerable success, smart wearables, [10]–[14], have become pivotal in reshaping applications within the health sector, fitness regimens, and industrial environments. Their versatile functionality overcomes conventional boundaries, positioning them as necessary tools for improving personal well-being, fueling fitness routines, and optimizing productivity in various industrial applications. Integration of conformal antennas has found practical application in smart devices, particularly in smart watches [15]–[18] smart phones, [19]–[22], solar panels [23]. Designing antennas for XR applications presents several specific challenges due to the unique requirements of XR devices. XR is considered as a main component of the metaverse services [24], [25]. High antenna gain is crucial for reliable communication in the metaverse, where seamless interactions are key. High gain enables stronger signals, extended range, and reduce the interference. Morever, utilizing the PhC antenna with high gain

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and efficiency into XR devices not only enhances their performance but also offers a significant advantage in power management. PhC antenna with high gain focus signals directionally, reducing signal loss and interference. This minimizes the need for extra signal processing or amplification, enhancing efficiency. High gain antennas enhance signal-to-noise ratio (SNR) by concentrating energy, further reducing processing and amplification needs, thus lowering power consumption and heat generation.This reduction in heat generation is crucial for maintaining optimal operating conditions and extending the lifespan of the device components [26]. Operating in the millimeter range provides significant advantages for XR communication [27]. Shorter wavelengths enable compact, high-gain antennas, perfect for portable metaverse devices. Utilizing Frequency Range 2 (FR2), including bands like n257 and n259, ensures compatibility with 5G NR and facilitates seamless transmission within the millimeter-wave band. Additionally, mmWave frequencies enable the transmission of large data volumes necessary for high-resolution XR experiences, supporting quick data transfer and high-quality audio and video streaming. Moreover, the relatively unused spectrum in this range potentially leads to better signal quality, reduced interference and improved performance, ultimately enhancing capacity and enabling more simultaneous connections. XR is thus regarded as a key component of metaverse services, ensuring uninterrupted and immersive user experiences [28].

The proposed antenna is a slot antenna. These antennas are notable for their planar configuration, widely utilized in various wireless communication applications due to their compact size and ease of integration with printed circuit boards. This becomes particularly important while navigating the complex world of XR communication, as flexibility and adaptation are critical. Slot antennas meet the challenges of a transforming telecom industry ecosystem by increasing the efficiency of XR systems while functioning in the 26.08-27.92 GHz and 39.65-43.27 GHz frequency bands. As such, the combination of XR with cutting-edge antenna technologies sets the stage for dependable wireless communication, uninterrupted connectivity, and immersive experiences that will revolutionize the fundamental structure of a globally interconnected world.

To explore the rest of this paper, the following sections are organized as: Section II explores the integration of PhC-enhanced antennas for enhanced performance, with a specific emphasis on the future prospects and implications of PhC-enhanced antennas in XR communications. Section III addresses aspects of antenna design and includes performance analysis (by emphasizing key findings and implications). The reflection coefficient (S11) plot for dual resonance bands, radiation pattern plot, and gain plot are examined, together with the 3D radiation pattern. Section IV introduces our antenna, showcasing its compact design, 5G performance, and potential for advancing communication technologies and XR experiences. Finally, Section V not only presents the conclusions and summarizes the findings of the work, by providing an overview of the key contributions, but also briefly presents proposals for future research.

II. Integration of PhC-Enhanced Antennas for Enhanced Performance

PhC are periodic structures that exhibit unique optical properties due to their ability to control the propagation of light and electromagnetic waves [29]. These structures are composed of materials with alternating high and low refractive indexes, forming a periodic lattice. Creating PhC by introducing holes in the substrate of antenna is a technique known as substrate-integrated PhC design. The shape, size, and arrangement of the holes determine the optical properties of the PhC. By incorporating PhC into antenna designs, several advantages can be achieved. One of the advantages of using PhC in antenna design is the creation of a Photonic Band Gap (PBG). PBG structures are formed through the arrangement of dielectric materials in a periodic manner. This arrangement creates regions within the material where certain frequencies of light are unable to propagate. These forbidden frequency ranges are termed as PBG. By modifying the periodicity and geometry of the dielectric materials, as well as their refractive indexes, engineers can customize the properties of the PBG. Customization of the antenna design employing Photonic Crystal (PhC) encompasses adjustments in its width, position within the electromagnetic spectrum, and polarization dependence. Adapting the antenna design to various target frequencies necessitates several modifications. Notably, significant focus is placed on PBG materials due to their ability to confine and regulate electromagnetic waves within space [30]. Customization of the antenna design employing PhC encompasses adjustments in its width, position within the electromagnetic spectrum, and polarization dependence. Adapting the antenna design to various target frequencies necessitates several modifications. Notably, significant focus is placed on Photonic Band Gap (PBG) materials due to their ability to confine and regulate electromagnetic waves within space . This control allows PhC to control the direction, speed, and dispersion of electromagnetic waves, thereby minimizing losses and optimizing energy transfer in the antenna system. In addition, through precise design, PhC can generate PBG that selectively inhibit or attenuate undesired frequencies, thus decreasing interference and enhancing signal quality [31]. The integration of PhC antennas offers several advantages, including bandwidth enhancement, radiation pattern control and miniaturization.

III. ANTENNA DESIGN AND PERFORMANCE ANALYSIS

The integration of Photonic Crystal (PhC) into the design of the antenna enhances the control and manipulation of electromagnetic waves. The resonant band, coupled with a substantial gain increase, significantly enhances the performance of the antenna by amplifying transmitted signal strength, while simultaneously improving signal reception. The choice of a PhC substrate over the conventional substrate is made to enhance antenna directivity and efficiency, as well as to prevent substrate surface path loss [32].

Whilst seeking optimal antenna performance, the choice of substrate materials are of fundamental importance. In this study, the substrate selected was RT/Duroid 5880, known for its high performance and reliability, providing an acceptable appropriate foundation solution for the antenna structure. Copper, chosen for its excellent conductivity, was employed in crafting the patch antenna with a thickness of 35 μm. This precise selection of materials aims to enhance the overall efficiency and responsiveness of the antenna, ensuring seamless integration into XR communication systems. Detailed information about the antenna geometry is presented in Fig. 1.

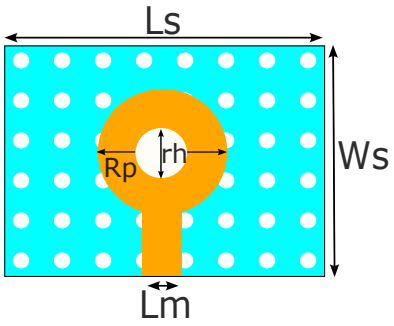

Fig. 1. Antenna geometry: Configuration of antenna based photonic crystal.

Table I provides a comprehensive overview of size parameters. Fundamental aspects like the improvement in the radiation pattern, reflection coefficient (S11) plot, and gain plot highlight the effectiveness of our multi-band antenna in XR communications, showcasing the advantages of integrating PhC in its design and fabrication. It is a step toward creating antennas that perform better and contribute to improved XR experiences.

TABLE I
SIZE PARAMETERS TABLE: DETAILING THE DIMENSION AND SPECIFICATION OF KEY PARAMETERS.

Parameter	Value [μm]
Ls	7320
Ws	6120
Rp	1720
Lm	745
rh	300

The reflection coefficient (S11) plot, as shown in Fig. 2, is a crucial chart to understand the PhC antenna resonance characteristics. The presence of two distinct resonance bands at specific frequencies, such as 27.0 GHz and 41.49 GHz, aligns with the targeted frequency requirements of XR communications.

Fig. 3 illustrates the S11 plot of antenna without PhC substrate, showcasing a distinct resonance band, by a notable reduction in antenna bandwidth. This representation emphasizes the influence of the absence of a PhC on the performance characteristics of the antenna. It is noteworthy that the bandwidth of this antenna is 1.20 GHz, with the resonance band occurring at 39.15 GHz.

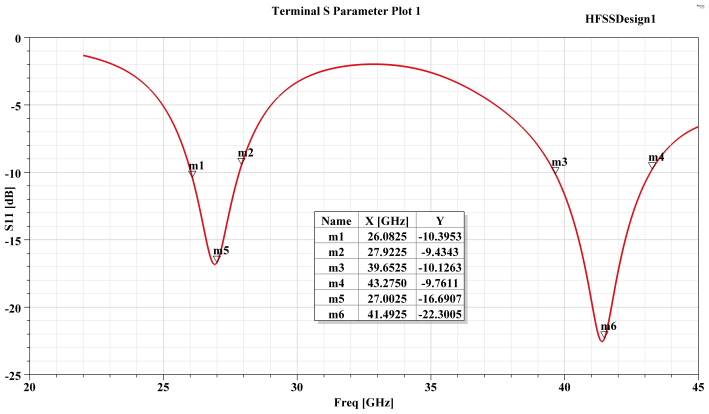

Fig. 2. Reflection coefficient plot illustrating dual resonance bands in photonic crystal antenna.

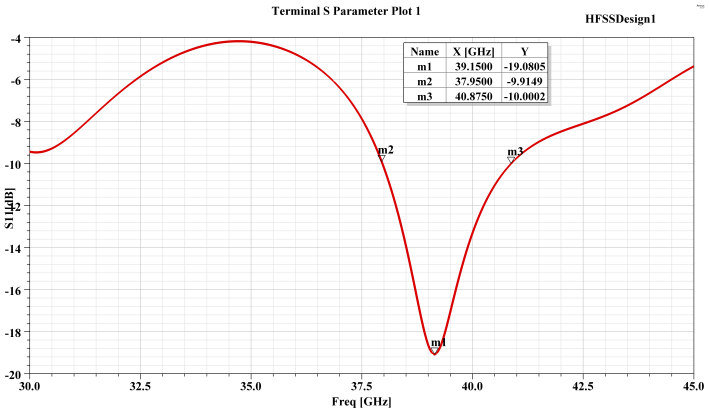

Fig. 3. Reflection coefficient plot illustrating a resonance band in an antenna without photonic crystal substrate.

The radiation pattern in Fig. 4, shows the directional properties of the proposed PhC antenna at 27 GHz, showcasing its ability to focus and direction of signals. Fig. 5 illustrates the radiation pattern at the resonant frequency of 41 GHz. Fig. 6, shows the antenna gain plot without PhC, indicating a value of 4.92 dBd. In comparison, Fig. 7, representing the antenna gain plot with PhC, demonstrates a noticeable decrease in gain for the antenna without a PhC. In addition, the use of the PhC enhances the antenna's directionality, contributing to the observed higher gain. The design consists of PhC optimizes the antenna ability to concentrate its radiation in specific directions, resulting in a more efficient and focused signal transmission. This notable improvement in gain and directional characteristics underline the significant impact of integrating PhC into the antenna design. It provides valuable insights for antenna optimization, emphasizing the potential for enhanced performance in applications where superior gain and directional accuracy are important.

The gain plot, as shown in Fig. 7, provides a quantitative measure of the antenna's ability to amplify signal strength. The antenna gain is 7.42 dBd, confirming its efficiency in enhancing the power and effectiveness of signal transmission

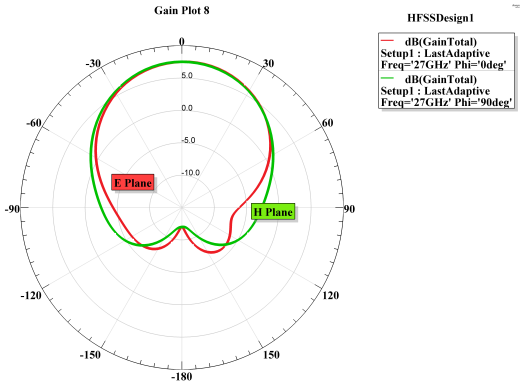

Fig. 4. Radiation Pattern at 27 GHz: Highlighting the antenna's signal directionality and concentration for optimal performance in the designated frequency band.

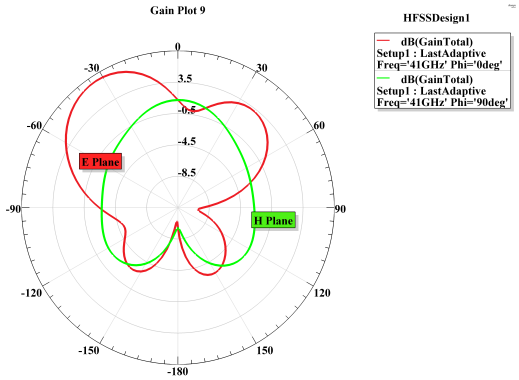

Fig. 5. Radiation Pattern at 41 GHz: Demonstrating the antenna's ability to focus and steer signals effectively within the 41GHz frequency range.

and reception. In the case of XR communication, a higher gain is important for achieving reliability.

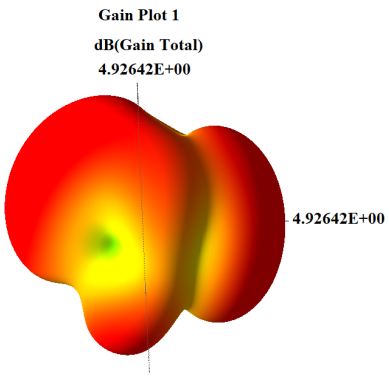

Fig. 6. Efficiency Comparison: Illustrating antenna gain in dBd, highlighting the impact of the PhC for enhanced performance.

Including the antenna 3D radiation pattern in the analysis improves our understanding of signal behavior, antenna design engineers use this visual insight to enhance antenna design for optimal performance, as demonstrated in Fig. 8. The real-

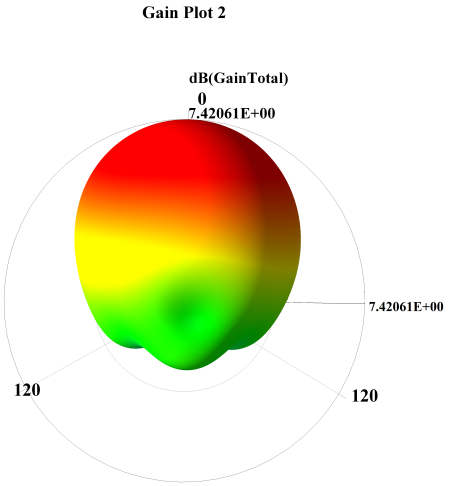

Fig. 7. Gain Plot: Showcasing the PhC antenna efficiency in 27 GHz in dBd.

world application of the 3D pattern provides valuable insights, supporting informed decision-making during the antenna design and deployment.

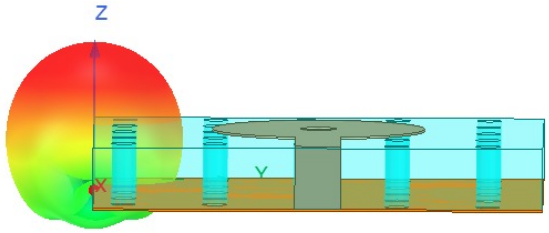

Fig. 8. Integrating the 3D radiation pattern atop the antenna in the analysis.

TABLE II
COMPARISON IS CONDUCTED BETWEEN THE ANTENNA PARAMETERS PRESENTED AND THOSE REPORTED IN PREVIOUS STUDIES.

Methods	f GHz	Gain (dBd)	S_{11} (dB)	B.W (GHz)	Ref.
FEM (HFSS)	28	5.35	-20.59	2.8	[33]
	2.4 5.2	5.09 6.78	- -	0.3 0.37	[34]
	28.04	5.87	-13.83	0.18	[35]
	2.66 4.8	3.46 4.59	- -	0.2 0.66	[36]
	2.4 5.75	0.87 5.77	- -	0.02 0.07	[37]
	27.0 41.49	7.42 6.76	-17.41 -23.70	1.84 3.62	This Work

Table II, presents a comparison of antenna parameters between the proposed design in this study and those reported in previous studies. As is apparent from the table, the proposed antenna showcases a broader bandwidth and higher gain compared to the antennas reported in previous studies, further exhibiting the distinctive feature of dual resonance bands.

In recent years, the field of computational electromagnetic modeling (CEM) has seen the emergence of diverse numerical methods, categorized into differential and integral equation approaches. These methods include the green function method,

finite integration techniques (FIT), finite element method (FEM), method of moments (MoM), finite-difference time-domain (FDTD), and others. Our chosen software for this study is High-Frequency Structure Simulator (HFSS), which relies on the FEM for calculations.Within the realm of antenna design, FEM acts as a powerful tool for simulating and optimizing performance. It aids researchers and engineers in understanding how antennas interact with electromagnetic fields and physical structures, leading to improved designs and enhanced overall performance. FEM is instrumental in solving Maxwell's equations, describing the behavior of electric and magnetic fields in the presence of physical boundaries. The process involves dividing the domain into finite elements, assigning electromagnetic properties, and applying numerical techniques to solve the resulting equations. These elements subdivide the domain into sub-domains (mesh), adopting shapes such as triangles or quadrangles for two-dimensional problems and prisms, hexahedra, or tetrahedra for three-dimensional problems. This enables accurate modeling and analysis of electromagnetic phenomena, covering antenna characteristics like gain, radiation pattern, and impedance. FEM utilizes finite elements to discretize the structure into smaller subsections, optimizing the solution for electric and magnetic fields. Conversely, FIT discretizes both space and time using a mesh for spatial sampling and a time step for temporal sampling. Both FEM and FIT play significant roles in simulating electromagnetic phenomena and improving antenna designs.

IV. Statement of novelty

The proposed antenna in this study, with its compact size, performs exceptionally well in 5G wireless communication applications, providing high radiation performance with a bandwidth of approximately 5.46 GHz and a gain of 7.42 dBd. The multi-resonant capability, coupled with high gain, positions it as a promising solution for next-generation communication systems. PhC significantly enhance antenna performance by enabling efficient wave control and resonance at smaller dimensions, resulting in compact, high-performing antennas. Their manipulation of effective characteristics are pivotal in achieving exceptional performance without compromising efficiency. In the realm of high-performing antennas, efficiency, directivity, wide bandwidth, high gain, and compact design are critical characteristics. To further enhance antenna performance and achieve compact size, we opted for PhC substrate instead of a conventional uniform substrate. This choice effectively prevents substrate surface path loss, resulting in improved antenna directivity and efficiency. As mentioned in the text, the difference between the diagrams of the antennas, with and without the PhC substrate, clearly shows the advantages of the former ones. As a consequence, this work provides valuable insights to discussions about the convergence between photonic and communications technologies, aiding in the enhancement of XR experiences characterized by their intrinsic reliability and efficiency width mobile communications share toward and a harmonious fusion of antenna radiation and innovation.

V. Conclusion

With resonant band coverage at 27.0 GHz and 41.49 GHz and a gain of 9.57 dBi, the PhC antenna presented in this paper operates within the millimeter-wave frequency range (n257 and n259). The millimeter-wave frequency band offers several advantages for XR applications. Firstly, it provides high bandwidth to support high-data rate transfer, making it suitable for delivering immersive virtual reality experiences and real-time augmented reality coverse. The wide bandwidth facilitates the transmission of significant amounts of data, such as high-definition video streams and complex 3D models, enhancing the visual quality and resolution of XR content. Furthermore,The shorter wavelengths associated with these frequencies enable the development of small-sized antennas, which are crucial for portable metaverse devices. Compact antennas facilitate seamless integration into XR headsets, glasses, or other wearable devices, providing users with a more comfortable and practical XR experience. The gain of 9.57 dBi achieved by the PhC antenna signifies its ability to focus and amplify the transmitted or received signals within the specified frequency bands. This high gain enhances the signal strength, extends the communication range, and improves overall system performance in the metaverse. Reliable and robust communication is essential for seamless interactions within the XR environment, and the high gain of the antenna contributes to achieving this goal.

The antenna bandwidth coverage at 26.08-27.92 GHz and 39.65-43.27 GHz, along with the gain of 9.57 dBi, makes the PhC antenna well-suited for XR applications in the metaverse. As the metaverse continues to evolve and expand, the integration of PhC, multiple-input multiple-output (MIMO) technology, and beamforming techniques into XR communications holds great promise. This integrated approach will further enhance signal quality, enable customized antenna designs for XR devices, reduce latency, and improve energy efficiency, ultimately advancing the metaverse experience.

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